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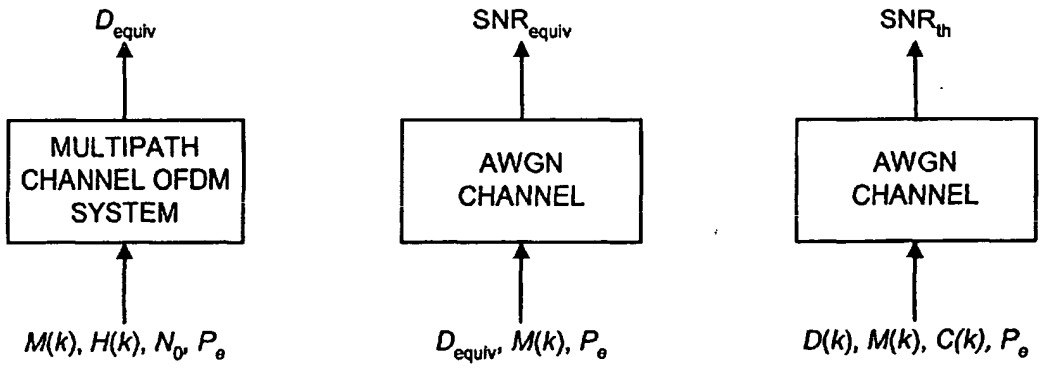
(54) Title: RATE SELECTION FOR AN OFDM SYSTEM



$D_{equiv}=f[x]$, $x=\{H(k), N_0, M(k)\}$ $\quad SNR_{equiv}=g[D_{equiv}, M(k)]$

(57) Abstract: Techniques to determine the rate for a data transmission in an OFDM system. The maximum data rate that may be reliably transmitted over a given multipath (non-flat) channel by the OFDM system is determined based on a metric for an equivalent (flat) channel. For the given multipath channel and a particular rate (which may be indicative of a particular data rate, modulation scheme, and coding rate), the metric is initially derived from an equivalent data rate and the particular modulation scheme. A threshold SNR needed to reliably transmit the particular data rate using the particular modulation scheme and coding rate is then determined. The particular rate is deemed as being supported by the multipath channel if the metric is greater than or equal to the threshold SNR. Incremental transmission is used to account for errors in the determined data rate.

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RATE SELECTION FOR AN OFDM SYSTEM

CROSS REFERENCE

[1001] This application is a continuation-in-part of co-pending Application Serial Number 09/991,039, filed November 21, 2001, entitled "RATE SELECTION FOR AN OFDM SYSTEM," and currently assigned to the assignee of the present application.

BACKGROUND

Field

[1002] The present invention relates generally to data communication, and more specifically to techniques for selecting rate for a wireless (e.g., OFDM) communication system.

Background

[1003] Wireless communication systems are widely deployed to provide various types of communication such as voice, data, and so on. These systems may implement orthogonal frequency division multiplex (OFDM) modulation, which may be capable of providing high performance for some channel environments. In an OFDM system, the system bandwidth is effectively partitioned into a number of (NF) frequency subchannels (which may be referred to as sub-bands or frequency bins). Each frequency subchannel is associated with a respective subcarrier (or frequency tone) upon which data may be modulated. Typically, the data to be transmitted (i.e., the information bits) is encoded with a particular coding scheme to generate coded bits, and the coded bits may further be grouped into multi-bit symbols that are then mapped to modulation symbols based on a particular modulation scheme (e.g., M-PSK or M-QAM). At each time interval that may be dependent on the bandwidth of each frequency subchannel, a modulation symbol may be transmitted on each of the NF frequency subchannels.

[1004] The frequency subchannels of an OFDM system may experience different channel conditions (e.g., different fading and multipath effects) and may achieve different signal-to-noise-and-interference ratios (SNRs). Each transmitted modulation symbol is affected by the frequency response of the communication channel at the particular frequency subchannel via which the symbol was transmitted. Depending on the multipath profile of the communication channel, the frequency response may vary widely throughout the system bandwidth. Thus, the modulation symbols that collectively form a particular data packet may be individually received with a wide range of SNRs via the NF frequency subchannels, and the SNR would then vary correspondingly across the entire packet.

[1005] For a multipath channel having a frequency response that is not flat or constant, the number of information bits per modulation symbol (i.e., the data rate or information rate) that may be reliably transmitted on each frequency subchannel may be different from subchannel to subchannel. Moreover, the channel conditions typically vary over time. As a result, the supported data rates for the frequency subchannels also vary over time.

[1006] Since the channel conditions experienced by a given receiver are typically not known a priori, it is impractical to transmit data at the same transmit power and/or data rate to all receivers. Fixing these transmission parameters would likely result in a waste of transmit power, the use of sub-optimal data rates for some receivers, and unreliable communication for some other receivers, all of which leads to an undesirable decrease in system capacity. The different transmission capabilities of the communication channels for different receivers plus the time-variant and multipath nature of these channels make it challenging to effectively code and modulate data for transmission in an OFDM system.

[1007] There is therefore a need in the art for techniques to select the proper rate for data transmission in a wireless (e.g., OFDM) communication system having the channel characteristics described above.

BRIEF DESCRIPTION OF THE DRAWINGS

[1008] The features, nature, and advantages of the present invention will become more apparent from the detailed description set forth below when taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

[1009] FIG. 1A is a diagram of a simplified model of an OFDM communication system;

[1010] FIG. 1B is a diagram that graphically illustrates rate selection for a multipath channel using an equivalent channel;

[1011] FIG. 2 is a flow diagram of an embodiment of a process for selecting data rate for use in the OFDM system based on a metric Ψ;

[1012] FIG. 3 is a block diagram of an embodiment of a transmitter system and a receiver system, which are capable of implementing various aspects and embodiments of the invention;

[1013] FIG. 4 is a block diagram of an embodiment of a transmitter unit;

[1014] FIG. 5 is a block diagram of an embodiment of a receiver unit;

[1015] FIG. 6 is a flow diagram of a Constrained Capacity Rate Adaptation (CCRA) algorithm;

[1016] FIGs. 7A-7D are flow diagrams of a Modified-CCRA (M-CCRA) algorithm; and

[1017] FIG. 8 is a graphical comparison of performance of the CCRA algorithm to an ideal rate selection.

DETAILED DESCRIPTION

[1018] The techniques described herein for determining and selecting the rate for a data transmission may be used for various wireless communication systems comprising one or more independent transmission channels, e.g., multiple-input multiple-output (MIMO) systems. For clarity, various aspects and embodiments of the invention are described specifically for an orthogonal frequency division multiplex (OFDM) system, where the independent transmission channels are the frequency subchannels or bins formed by dividing the total system bandwidth.

[1019] FIG. 1A is a diagram of a simplified model of the OFDM system. At a transmitter 110, traffic data is provided at a particular data rate from a data source 112 to an encoder/modulator 114, which codes the data in accordance with one or more coding schemes and further modulates the coded data in accordance with one or more modulation schemes. The modulation may be achieved by grouping sets of coded bits to form multi-bit symbols and mapping each multi-bit symbol to a point in a signal constellation corresponding to the particular modulation scheme (e.g., QPSK, M-PSK, or M-QAM) selected for each frequency subchannel used to transmit the symbol. Each mapped signal point corresponds to a modulation symbol.

[1020] In an embodiment, the data rate is determined by a data rate control, the coding scheme(s) are determined by a coding control, and the modulation scheme(s) are determined by a modulation control, all of which are provided by a controller 130 based on feedback information received from a receiver 150.

[1021] A pilot may also be transmitted to the receiver to assist it perform a number of functions such as channel estimation, acquisition, frequency and timing synchronization, coherent data demodulation, and so on. In this case, pilot data is provided to encoder/modulator 114, which then multiplexes and processes the pilot data with the traffic data.

[1022] For OFDM, the modulated data (i.e., the modulation symbols) is then transformed to the time domain by an inverse fast Fourier transformer (IFFT) 116 to provide OFDM symbols, with each OFDM symbol corresponding to a time representation of a vector of N_F modulation symbols to be transmitted on N_F frequency subchannels in a transmission symbol period. In contrast to a single carrier "time-coded" system, the OFDM system effectively transmits the modulation symbols "in the frequency domain", by sending in the time domain the IFFT of the modulation symbols that represent the traffic data. The OFDM symbols are further processed (not shown in FIG. 1A for simplicity) to generate a modulated signal, which is then transmitted over a wireless communication channel to the receiver. As shown in FIG. 1A, the communication channel has a frequency response of $H(f)$ and further degrades the modulated signal with additive white Gaussian noise (AWGN) of $n(t)$.

[1023] At receiver 150, the transmitted modulated signal is received, conditioned, and digitized to provide data samples. A fast Fourier transformer (FFT) 160 then receives and transforms the data samples to the frequency domain, and the recovered OFDM symbols are provided to a demodulator/decoder 162 and a channel estimator 164. Demodulator/decoder 162 processes (e.g., demodulates and decodes) the recovered OFDM symbols to provide decoded data, and may further provide a status of each received packet. Channel estimator 164 processes the recovered OFDM symbols to provide estimates of one or more characteristics of the communication channel, such as the channel frequency response, the channel noise variance, the signal-to-noise-and-interference ratio (SNR) of the received symbols, and so on.

[1024] A rate selector 166 receives the estimates from channel estimator 164 and determines a suitable "rate" that may be used for all or a subset of the frequency subchannels available for use for data transmission. The rate is indicative of a set of specific values for a set of parameters. For example, the rate may indicate (or may be associated with) a specific data rate to be used for the data transmission, a specific coding scheme and/or coding rate, a specific modulation scheme, and so on.

[1025] A controller 170 receives the rate from rate selector 166 and the packet status from demodulator/decoder 162 and provides the appropriate feedback information to be sent back to transmitter 110. This feedback information may include the rate, the channel estimates provided by channel estimator 164, an acknowledgment (ACK) or negative acknowledgment (NACK) for each received packet, some other information, or any combination thereof. The feedback information is used to increase the efficiency of the system by adjusting the data processing at the transmitter such that the data transmission is performed at the best known settings of power and rate that may be supported by the communication channel. The feedback information is then sent back to transmitter 110 and used to adjust the processing (e.g., the data rate, coding, and modulation) of the data transmission to receiver 150.

[1026] In the embodiment shown in FIG. 1A, the rate selection is performed by receiver 150 and the selected rate is provided to transmitter 110. In other embodiments, the rate selection may be performed by the transmitter based on

feedback information provided by the receiver, or may be performed jointly by both the transmitter and receiver.

[1027] Under suitable conditions, the recovered OFDM symbols at the output of FFT 160 may be expressed as:

$$\hat{Y}(k) = Y(k)H(k) + N(k) \quad , \qquad \text{Eq (1)}$$

[1028] where k is an index for the frequency subchannels of the OFDM system, i.e., $k = 0, 1, \ldots, N_F - 1$, where N_F is the number of frequency subchannels;

[1029] $Y(k)$ are the modulation symbols transmitted on the k-th frequency subchannel, which are derived based on a particular modulation scheme used for the k-th frequency subchannel;

[1030] $H(k)$ is the frequency response of the communication channel, represented in "quantized" form for each frequency subchannel;

[1031] $N(k)$ represents the FFT of a sequence of N_F samples of the time-domain noise, i.e., $\mathrm{FFT}\{n(kT)\}$ for $k = 0, 1, \ldots, N_F - 1$; and T is the sampling period.

[1032] In a single carrier system, the transmitted symbols may all be received at the receiver at approximately the same SNR. The relationship between the SNR of a "constant SNR" packet and the probability of error for the packet is well known in the art. As an approximation, the maximum data rate supported by the single carrier system with a particular achieved SNR may be estimated as the maximum data rate supported by an AWGN channel with the same SNR. The main characteristic of the AWGN channel is that its frequency response is flat or constant across the entire system bandwidth.

[1033] However, in an OFDM system, the modulation symbols that make up a packet are transmitted across multiple frequency subchannels. Depending on the frequency response of the frequency subchannels used to transmit the packet, the SNR may vary across the entire packet. This problem of "varying SNR" packet is exacerbated as the system bandwidth increases and for a multipath environment.

[1034] A major challenge for an OFDM system is then to determine the maximum data rate that may be used for data transmission while achieving a

particular level of performance, which may be quantified by a particular packet error rate (PER), frame error rate (FER), bit error rate (BER), or some other criterion. For example, the desired level of performance may be achieved by maintaining the PER within a small window around a particular nominal value (e.g., $P_e = 1\%$).

[1035] In a typical communication system, a set of specific and discrete data rates may be defined, and only these data rates may be available for use. Each data rate, $D(r)$, may be associated with a specific modulation scheme or constellation, $M(r)$, and a specific coding rate, $C(r)$. Each data rate would further require a particular $\mathrm{SNR}(r)$, which is the minimum SNR at which the resulting PER for the data transmission at that data rate is less than or equal to the desired PER, P_e. This $\mathrm{SNR}(r)$ assumes that the communication channel is AWGN (i.e., with a flat frequency response across the entire system bandwidth, or $H(k) = H$ for all k). Typically, the communication channel between the transmitter and receiver is not AWGN, but is instead dispersive or frequency selective (i.e., different amounts of attenuation at different sub-bands of the system bandwidth). For such a multipath channel, the particular data rate to be used for data transmission may be selected to account for the multipath or frequency selective nature of the channel.

[1036] Each data rate, $D(r)$, may thus be associated with a set of parameters that characterizes it. These parameters may include the modulation scheme $M(r)$, the coding rate $C(r)$, and the required $\mathrm{SNR}(r)$, as follows:

$$D(r) \leftrightarrow [M(r),\ C(r),\ \mathrm{SNR}(r)] \ , \qquad \text{Eq (2)}$$

[1037] where r is an index for the data rates, i.e., $r = 0, 1, \ldots, \mathrm{N_R} - 1$, where $\mathrm{N_R}$ is the total number of data rates available for use. Equation (2) states that data rate $D(r)$ may be transmitted using modulation scheme $M(r)$ and coding rate $C(r)$ and further requires $\mathrm{SNR}(r)$ in an AWGN channel to achieve the desired nominal PER P_e. The $\mathrm{N_R}$ data rates may be ordered such that $D(0) < D(1) < D(2) \ldots < D(\mathrm{N_R} - 1)$.

[1038] In accordance with an aspect of the invention, the maximum data rate that may be reliably transmitted over a given multipath channel in an OFDM

system is determined based on a metric for an equivalent AWGN channel. Reliable transmission is achieved if the desired PER of P_e is maintained for the data transmission. Details of this aspect are described below.

[1039] FIG. 1B is a diagram that graphically illustrates the rate selection for a multipath channel using an equivalent channel. For a given multipath channel defined by a channel response of $H(k)$ and a noise variance of N_0, the OFDM system may be capable of achieving an equivalent data rate of D_{equiv} using modulation scheme $M(k)$, where $M(k)$ may be different for different frequency subchannels. This D_{equiv} may be estimated as described below based on a particular channel capacity function $f[H(k), N_0, M(k)]$. Since the bandwidth of each individual frequency subchannel is normalized to 1, it does not appear as an argument of the function $f[\cdot]$. The metric, which is an estimate of the SNR, SNR_{equiv}, required by an equivalent AWGN channel to transmit at the equivalent data rate of D_{equiv} using modulation scheme $M(k)$ at the desired PER of P_e, may be derived for D_{equiv} using $M(k)$ and further based on a function $g(D_{equiv}, M(k))$ that is also described below.

[1040] For a data rate $D(k)$, modulation scheme $M(k)$, and coding rate $C(k)$, the AWGN channel would need an SNR of SNR_{th} or better to achieve the desired PER of P_e. This threshold SNR_{th} may be determined by computer simulation or some other means. The data rate $D(k)$ may then be deemed as being supported by the OFDM system for the multipath channel if the metric (or SNR_{equiv}) is equal to or greater than SNR_{th}. As the data rate $D(k)$ increases, the threshold SNR_{th} increases for the given channel conditions defined by $H(k)$ and N_0. The maximum data rate that may be supported by the OFDM system is thus limited by the channel conditions. Various schemes are provided herein to determine the maximum data rate that may be supported by the OFDM system for the given multipath channel. Some of these schemes are described below.

[1041] In a first rate selection scheme, the metric Ψ receives a set of parameters for a data transmission on a given multipath channel in an OFDM system and, based on the received parameters, provides an estimate of the SNR for an AWGN channel equivalent to the multipath channel. These input

parameters to the metric Ψ may include one or more parameters related to the processing of the data transmission (e.g., the modulation scheme $M(k)$) and one or more parameters related to the communication channel (e.g., the channel response $H(k)$ and the noise variance N_0). As noted above, the modulation scheme $M(k)$ may be associated with a specific data rate $D(k)$. The metric Ψ is the estimate of the SNR of the equivalent AWGN channel (i.e., $\Psi \approx \mathrm{SNR}_{\mathrm{equiv}}$). The maximum data rate supported by the multipath channel may then be determined as the highest data rate associated with an equivalent SNR that is greater than or equal to the threshold SNR, $\mathrm{SNR}_{\mathrm{th}}$, required on the AWGN channel to achieve the desired PER of P_e using the coding and modulation schemes associated with the data rate.

[1042] Various functions may be used for the metric Ψ, some of which are provided below. In an embodiment, the metric Ψ is defined as:

$$\Psi = g\left\{\left(\sum_{k=0}^{N_F-1} f[H(k), N_0, M]\right), M\right\} . \qquad \text{Eq (3)}$$

[1043] In equation (3), the function $f[H(k), N_0, M]$ determines the maximum data rate that modulation scheme M can carry on the k-th frequency subchannel with the frequency response $H(k)$ and the noise variance N_0. The function $f[H(k), N_0, M]$ may be defined based on various channel capacity functions, as described below.

[1044] The parameters $H(k)$ and N_0 may be mapped to an $\mathrm{SNR}(k)$. If the total transmit power, P_{total}, for the system is fixed and the allocation of the transmit power to the N_F frequency subchannels is uniform and fixed, then the SNR for each frequency subchannel may be expressed as:

$$\mathrm{SNR}(k) = \frac{P_{\mathrm{total}}}{N_F} \frac{|H(k)|^2}{N_0} . \qquad \text{Eq (4)}$$

[1045] As shown in equation (4), $\mathrm{SNR}(k)$ is a function of the channel response $H(k)$ and the noise variance N_0, which are two of the parameters of the function $f[H(k), N_0, M]$.

[1046] The summation in equation (3) is performed for $f[\cdot]$ over all N_F frequency subchannels to provide the equivalent data rate D_{equiv} that may be transmitted on the AWGN channel. The function $g(D_{equiv}, M)$ then determines the SNR needed in the AWGN channel to reliably transmit at the equivalent data rate D_{equiv} using the modulation scheme *M*.

[1047] Equation (3) assumes that the same modulation scheme *M* is used for all N_F frequency subchannels in the OFDM system. This restriction results in simplified processing at the transmitter and receiver in the OFDM system but may sacrifice performance.

[1048] If different modulation schemes may be used for different frequency subchannels, then the metric Ψ may be defined as:

$$\Psi = \sum_{k=0}^{N_F-1} g\left(f[H(k), N_0, M(k)], M(k)\right) . \qquad \text{Eq (5)}$$

[1049] As shown in equation (5), the modulation scheme, *M*(*k*), is a function of the index *k* of the frequency subchannels. The use of different modulation schemes and/or coding rates for different frequency subchannels is also referred to as "bit loading".

[1050] The function $f[x]$ determines the data rate that may be reliably transmitted over the AWGN channel for a set of parameters collectively represented as *x*, where *x* may be a function of frequency (i.e., *x*(*k*)). In equation (5), the function $f[H(k), N_0, M(k)]$, where $x(k) = \{H(k), N_0, M(k)\}$, determines the data rate that modulation scheme $M(k)$ can carry on the *k*-th frequency subchannel with the channel response *H*(*k*) and the noise variance N_0. The function $g(f[x(k)], M(k))$ then determines the SNR needed in the equivalent AWGN channel to carry the data rate determined by $f[x(k)]$. The summation in equation (5) is then performed for $g(f[x(k)], M(k))$ over all N_F frequency subchannels to provide the estimate of the SNR for the equivalent AWGN channel, SNR_{equiv}.

[1051] The function $f[x]$ may be defined based on various channel capacity functions or some other functions or techniques. The absolute capacity of a system is typically given as the theoretical maximum data rate that may be

reliably transmitted for the channel response $H(k)$ and the noise variance N_0. The "constrained" capacity of a system depends on the specific modulation scheme or constellation, $M(k)$, used for data transmission and is lower than the absolute capacity.

[1052] In one embodiment, the function $f[H(k),N_0,M(k)]$ is defined based on the constrained channel capacity function and may be expressed as:

$$f(k) = M_k - \frac{1}{2^{M_k}} \sum_{i=1}^{2^{M_k}} E\left[\log_2 \sum_{j=1}^{2^{M_k}} \exp\left(-\mathrm{SNR}(k)(|a_i - a_j|^2 + 2\mathrm{Re}\{x^*(a_i - a_j)\})\right)\right] , \quad \text{Eq (6)}$$

[1053] where M_k is related to the modulation scheme $M(k)$, i.e., the modulation scheme $M(k)$ corresponds to a 2^{M_k}-ary constellation (e.g., 2^{M_k}-ary QAM), where each of the 2^{M_k} points in the constellation may be identified by M_k bits;

a_i and a_j are the points in the 2^{M_k}-ary constellation;

x is a complex Gaussian random variable with zero mean and a variance of $1/\mathrm{SNR}(k)$; and

$E[\cdot]$ is the expectation operation, which is taken with respect to the variable x in equation (6).

[1054] The constrained channel capacity function shown in equation (6) does not have a closed form solution. Thus, this function may be numerically derived for various modulation schemes and SNR values, and the results may be stored to one or more tables. Thereafter, the function $f[x]$ may be evaluated by accessing the proper table with a specific modulation scheme and SNR.

[1055] In another embodiment, the function $f[x]$ is defined based on the Shannon (or theoretical) channel capacity function and may be expressed as:

$$f(k) = \log_2[1 + \mathrm{SNR}(k)] , \quad \text{Eq (7)}$$

where W is the system bandwidth. As shown in equation (7), the Shannon channel capacity is not constrained by any given modulation scheme (i.e., $M(k)$ is not a parameter in equation (7)).

[1056] The particular choice of function to use for $f[x]$ may be dependent on various factors, such as the OFDM system design. For a typical system that

employs one or more specific modulation schemes, it has been found that the matrix Ψ defined as shown in equation (3), when used in conjunction with the constrained channel capacity for the function $f[x]$ as shown in equation (6), is an accurate estimator of the maximum supported data rate for the OFDM system for the AWGN channel as well as for the multipath channel.

[1057] The function $g(f[x],M(k))$ determines the SNR needed in the AWGN channel to support the equivalent data rate, which is determined by the function $f[x]$, using the modulation scheme $M(k)$. In one embodiment, the function $g(f[x],M(k))$ is defined as:

$$g(f[x],M(k)) = f[x]^{-1} \quad . \qquad \text{Eq (8)}$$

[1058] Since the function $f[x]$ is dependent on the modulation scheme *M*(*k*), the function $g(f[x],M(k))$ is also dependent on the modulation scheme. In one implementation, the function $f[x]^{-1}$ may be derived for each modulation scheme that may be selected for use and may be stored to a respective table. The function $g(f[x],M(k))$ may then be evaluated for a given value of $f[x]$ by accessing the specific table for the modulation scheme *M*(*k*). The function $g(f[x],M(k))$ may also be defined using other functions or derived by other means, and this is within the scope of the invention.

[1059] FIG. 2 is a flow diagram of an embodiment of a process 200 for selecting data rate for use in the OFDM system based on the metric Ψ. Initially, the available data rates (i.e., those supported by the OFDM system) are ordered such that $D(0) < D(1) < \ldots < D(\mathrm{N_R}-1)$. The highest available data rate is then selected (e.g., by setting a rate variable to the index for the highest data rate, or $\mathrm{rate} = \mathrm{N_R}-1$), at step 212. Various parameters associated with the selected data rate *D*(rate), such as the modulation scheme *M*(rate), are then determined, at step 214. Depending on the design of the OFDM system, each data rate may be associated with one or multiple modulation schemes. Each modulation scheme of the selected data rate may then be evaluated based on the following step. For simplicity, the following assumes that only one modulation scheme is associated with each data rate.

[1060] The metric Ψ is then evaluated for the specific modulation scheme *M*(rate) associated with the selected data rate *D*(rate), at step 216. This may be

achieved by evaluating the function for the metric Ψ, as shown in equation (3), which is:

$$\Psi = g\left\{\left(\sum_{k=0}^{N_F-1} f[H(k), N_0, M(\text{rate})]\right), M(\text{rate})\right\} . \qquad \text{Eq (9)}$$

[1061] The metric Ψ represents an estimate of the SNR needed in the equivalent AWGN channel to reliably transmit the equivalent data rate using the modulation scheme *M*(rate).

[1062] The threshold SNR, $\text{SNR}_{\text{th}}(\text{rate})$, needed to transmit the selected data rate *D*(rate) with the desired PER of P_e in the AWGN channel is then determined, at step 218. The threshold $\text{SNR}_{\text{th}}(\text{rate})$ is a function of the modulation scheme *M*(rate) and the coding rate *C*(rate) associated with the selected data rate. The threshold SNR may be determined for each of the possible data rates via computer simulation or by some other means, and may be stored for later use.

[1063] A determination is then made whether or not the metric Ψ is greater than or equal to the threshold $\text{SNR}_{\text{th}}(\text{rate})$ associated with the selected data rate, at step 220. If the metric Ψ is greater than or equal to $\text{SNR}_{\text{th}}(\text{rate})$, which indicates that the SNR achieved by the OFDM system for the data rate *D*(rate) in the multipath channel is sufficient to achieve the desired PER of P_e, then that data rate is selected for use, at step 224. Otherwise, the next lower available data rate is selected for evaluation (e.g., by decrementing the rate variable by one, or $\text{rate} = \text{rate} - 1$), at step 222. The next lower data rate is then evaluated by returning to step 214. Steps 214 through 222 may be repeated as often as needed until the maximum supported data rate is identified and provided in step 222.

[1064] The metric Ψ is a monotonic function of data rate and increases with increasing data rate. The threshold SNR is also a monotonic function that increases with increasing data rate. The embodiment shown in FIG. 2 evaluates the available data rates, one at a time, from the maximum available data rate to the minimum available data rate. The highest data rate associated with a threshold SNR, $\text{SNR}_{\text{th}}(\text{rate})$, that is smaller than or equal to the metric Ψ is selected for use.

[1065] In another embodiment, the metric Ψ may be evaluated for a particular modulation scheme $M(r)$ to derive an estimate of the SNR for the equivalent AWGN channel, $\mathrm{SNR}_{\mathrm{equiv}}(r)$. The maximum data rate, $D_{\max}(r)$, supported by the AWGN channel for the desired PER at this equivalent SNR using the modulation scheme $M(r)$ is then determined (e.g., via a look-up table). The actual data rate to be used in the OFDM system for the multipath channel may then be selected to be less than or equal to the maximum data rate, $D_{\max}(r)$, supported by the AWGN channel.

[1066] In a second rate selection scheme, the metric Ψ is defined as a post-detection SNR achieved for the multipath channel by a single carrier system after equalization. The post-detection SNR is representative of the ratio of the total signal power to the noise plus interference after equalization at the receiver. Theoretical values of post-detection SNR achieved in the single carrier system with equalization may be indicative of the performance of an OFDM system, and therefore may be used to determine the maximum supported data rate in the OFDM system. Various types of equalizer may be used to process the received signal in the single carrier system to compensate for distortions in the received signal introduced by the multipath channel. Such equalizers may include, for example, a minimum mean square error linear equalizer (MMSE-LE), a decision feedback equalizer (DFE), and others.

[1067] The post-detection SNR for an (infinite-length) MMSE-LE may be expressed as:

$$\mathrm{SNR}_{mmse-le} = \frac{1 - J_{\min}}{J_{\min}} \quad , \qquad \text{Eq (10a)}$$

where $J_{\min}$ is given by

$$J_{\min} = \frac{T}{2\pi} \int_{-\pi/T}^{\pi/T} \frac{N_0}{X(e^{j\omega T}) + N_0} d\omega \quad , \qquad \text{Eq (10b)}$$

where $X(e^{j\omega T})$ is the folded spectrum of the channel transfer function $H(f)$.

[1068] The post-detection SNR for an (infinite-length) DFE may be expressed as:

$$\mathrm{SNR}_{dfe} = \exp\left[\frac{T}{2\pi} \int_{-\pi/T}^{\pi/T} \ln\left(\frac{X(e^{j\omega T}) + N_0}{N_0}\right) d\omega\right] - 1 \quad . \qquad \text{Eq (11)}$$

[1069] The post-detection SNRs for the MMSE-LE and DFE shown in equations (9) and (10), respectively, represent theoretical values. The post-detection SNRs for the MMSE-LE and DFE are also described in further detail by J. G. Proakis, in a book entitled "Digital Communications", 3rd Edition, 1995, McGraw Hill, sections 10-2-2 and 10-3-2, respectively, which are incorporated herein by reference.

[1070] The post-detection SNRs for the MMSE-LE and DFE may also be estimated at the receiver based on the received signal, as described in U.S. Patent Application Serial Nos. 09/826,481 and 09/956,449, both entitled "Method and Apparatus for Utilizing Channel State Information in a Wireless Communication System," respectively filed March 23, 2001 and September 18, 2001, and U.S. Patent Application Serial No. 09/854,235, entitled "Method and Apparatus for Processing Data in a Multiple-Input Multiple-Output (MIMO) Communication System Utilizing Channel State Information," filed May 11, 2001, all assigned to the assignee of the present application and incorporated herein by reference.

[1071] Post-detection SNRs, such as those described by the analytical expressions shown in equations (10) and (11), may be determined for the multipath channel and used as an estimate of the metric Ψ (i.e., $\Psi \approx \mathrm{SNR}_{mmse-le}$ or $\Psi \approx \mathrm{SNR}_{dfe}$). The post-detection SNR (e.g., $\mathrm{SNR}_{mmse-le}$ or SNR_{dfe}) for the equivalent AWGN channel may be compared against the threshold SNR, SNR_{th}, derived for a particular set of parameters, $D(r)$, $M(r)$, $C(r)$, and P_e, to determine the data rate that may be used in the OFDM system for the multipath channel.

[1072] The metric Ψ may also be defined based on some other functions, and the equivalent data rate may also be estimated based on some other techniques, and this is within the scope of the invention.

[1073] The data rate selected for use in the OFDM system based on the metric Ψ represents a prediction of the data rate that may be supported by the multipath channel for the desired PER of P_e. As with any rate prediction scheme, there will inevitably be prediction errors. In order to ensure that the desired PER can be achieved, the prediction errors may be estimated and a back-off factor may be used in determining the data rate that can be supported

by the multipath channel. This back-off reduces the throughput of the OFDM system. Thus, it is desirable to keep this back-off as small as possible while still achieving the desired PER.

[1074] In accordance with another aspect of the invention, an incremental transmission (IT) scheme is provided and may be advantageously used in conjunction with the rate selection of the first aspect to reduce the amount of back-off and to improve system throughput. The IT scheme transmits a given packet using one or more discrete transmissions, one transmission at a time and up to a particular limit. The first transmission for the packet includes sufficient amount of data such that the packet can be recovered error-free at the receiver based on the expected channel conditions. However, if the first transmission is excessively degraded by the communication channel such that error-free recovery of the packet is not achieved, then an incremental transmission of an additional amount of data for the packet is performed. The receiver then attempts to recover the packet based on the additional data in the incremental transmission and all data previously received for the packet. The incremental transmission by the transmitter and the decoding by the receiver may be attempted for one or more times, until the packet is recovered error-free or the maximum number of incremental transmissions is reached.

[1075] An embodiment of the IT scheme may be implemented as follows. First, the data for a packet is coded using a lower coding rate (for a forward error correction code) than the coding rate that may be used for the packet without any incremental transmission. Next, some of the coded bits for the packet are punctured and only a subset of all the coded bits is transmitted for the first transmission of the packet. If the packet is correctly received, then the receiver may send back an acknowledgement (ACK) indicating that the packet was received error-free. Alternatively, the receiver may send back a negative acknowledgement (NACK) if it receives the packet in error.

[1076] In either case, if the acknowledgement is not received by the transmitter for the packet or a negative acknowledgement is received, then the transmitter sends an incremental packet to the receiver. This incremental packet may include some of the original punctured coded bits that were not sent in the first transmission. The receiver then attempts to decode the packet by

using the coded bits sent in both the first transmission as well as the second transmission. The additional coded bits from the second transmission provide more energy and improve the error correction capability. One or more incremental transmissions may be performed, typically one at a time until the acknowledgement is received or the negative acknowledgement is not received.

[1077] If incremental transmission is employed by the system, then a smaller back-off may be used to account for rate prediction errors and more aggressive rate selections may be made. This may result in improved system throughput.

[1078] The incremental transmission in combination with the rate selection described above also provides an efficient mechanism for determining the maximum data rate supported by fixed or slow-varying communication channels. Consider a fixed-access application where the multipath profile of the channel changes slowly. In this case, an initial data rate may be selected based on the techniques described above and used for data transmission. If the initial data rate is higher than the channel can support, then the IT scheme can transmit additional coded bits until the packet can be correctly decoded at the receiver. The maximum data rate that the channel can support may then be determined based on the total number of coded bits sent in the first transmission and any subsequent incremental transmissions. If the channel changes slowly, then the determined data rate may be used until the channel changes, at which time a new data rate may be determined.

[1079] The incremental transmission thus provides numerous advantages. First, the use of incremental transmission allows for an aggressive data rate selection to increase system throughput. Second, incremental transmission provides a means for remedying prediction errors that inevitably arise for any rate prediction scheme (with the frequency and magnitude of the prediction errors being dependent on the amount of back-off employed). And third, incremental transmission provides a mechanism to more accurately determine the maximum supported data rate for fixed or slow-varying channels.

[1080] FIG. 3 is a block diagram of an embodiment of a transmitter system 110a and a receiver system 150a, which are capable of implementing various aspects and embodiments of the invention.

[1081] At transmitter system 110a, traffic data is provided at a particular data rate from a data source 308 to a transmit (TX) data processor 310, which formats, interleaves, and codes the traffic data based on a particular coding scheme to provide coded data. The data rate and the coding may be determined by a data rate control and a coding control, respectively, provided by a controller 330.

[1082] The coded data is then provided to a modulator 320, which may also receive pilot data (e.g., data of a known pattern and processed in a known manner, if at all). The pilot data may be multiplexed with the coded traffic data, e.g., using time division multiplex (TDM) or code division multiplex (CDM), in all or a subset of the frequency subchannels used to transmit the traffic data. In a specific embodiment, for OFDM, the processing by modulator 320 includes (1) modulating the received data with one or more modulation schemes, (2) transforming the modulated data to form OFDM symbols, and (3) appending a cyclic prefix to each OFDM symbol to form a corresponding transmission symbol. The modulation is performed based on a modulation control provided by controller 330. The modulated data (i.e., the transmission symbols) is then provided to a transmitter (TMTR) 322.

[1083] Transmitter 322 converts the modulated data into one or more analog signals and further conditions (e.g., amplifies, filters, and quadrature modulates) the analog signals to generate a modulated signal suitable for transmission over the communication channel. The modulated signal is then transmitted via an antenna 324 to the receiver system.

[1084] At receiver system 150a, the transmitted modulated signal is received by an antenna 352 and provided to a receiver (RCVR) 354. Receiver 354 conditions (e.g., filters, amplifies, and downconverts) the received signal and digitizes the conditioned signal to provide data samples. A demodulator (Demod) 360 then processes the data samples to provide demodulated data. For OFDM, the processing by demodulator 360 may include (1) removing the cyclic prefix previously appended to each OFDM symbol, (2) transforming each recovered OFDM symbol, and (3) demodulating the recovered modulation symbols in accordance with one or more demodulation schemes

complementary to the one or more modulation schemes used at the transmitter system.

[1085] A receive (RX) data processor 362 then decodes the demodulated data to recover the transmitted traffic data. The processing by demodulator 360 and RX data processor 362 is complementary to that performed by modulator 320 and TX data processor 310, respectively, at transmitter system 110a.

[1086] As shown in FIG. 3, demodulator 360 may derive estimates of the channel response, $\hat{H}(k)$, and provide these estimates to a controller 370. RX data processor 362 may also derive and provide the status of each received packet and may further provide one or more other performance metrics indicative of the decoded results. Based on the various types of information received from demodulator 360 and RX data processor 362, controller 370 may determine or select a particular rate for the data transmission based on the techniques described above. Feedback information in the form of a selected rate, the channel response estimates, ACK/NACK for the receive packet, and so on, may be provided by controller 370, processed by a TX data processor 378, modulated by a modulator 380, and conditioned and transmitted by a transmitter 354 back to transmitter system 110a.

[1087] At transmitter system 110a, the modulated signal from receiver system 150a is received by antenna 324, conditioned by a receiver 322, and demodulated by a demodulator 340 to recover the feedback information transmitted by the receiver system. The feedback information is then provided to controller 330 and used to control the processing of the data transmission to the receiver system. For example, the data rate of the data transmission may be determined based on the selected rate provided by the receiver system, or may be determined based on the channel response estimates from the receiver system. The specific coding and modulation schemes associated with the selected rate are determined and reflected in the coding and modulation control provided to TX data processor 310 and modulator 320. The received ACK/NACK may be used to initiate an incremental transmission (not shown in FIG. 3 for simplicity).

[1088] Controllers 330 and 370 direct the operation at the transmitter and receiver systems, respectively. Memories 332 and 372 provide storage for program codes and data used by controllers 330 and 370, respectively.

[1089] FIG. 4 is a block diagram of a transmitter unit 400, which is an embodiment of the transmitter portion of transmitter system 110a. Transmitter unit 400 includes (1) a TX data processor 310a that receives and processes traffic data to provide coded data and (2) a modulator 320a that modulates the coded data to provided modulated data. TX data processor 310a and modulator 320a are one embodiment of TX data processor 310 and modulator 320, respectively, in FIG. 3.

[1090] In the specific embodiment shown in FIG. 4, TX data processor 310a includes an encoder 412, a channel interleaver 414, and a puncturer 416. Encoder 412 receives and codes the traffic data in accordance with one or more coding schemes to provide coded bits. The coding increases the reliability of the data transmission. Each coding scheme may include any combination of CRC coding, convolutional coding, Turbo coding, block coding, and other coding, or no coding at all. The traffic data may be partitioned into packets (or frames), and each packet may be individually processed and transmitted. In an embodiment, for each packet, the data in the packet is used to generate a set of CRC bits, which is appended to the data, and the data and CRC bits are then coded with a convolutional code or a Turbo code to generate the coded data for the packet.

[1091] Channel interleaver 414 then interleaves the coded bits based on a particular interleaving scheme to provide diversity. The interleaving provides time diversity for the coded bits, permits the data to be transmitted based on an average SNR for the frequency subchannels used for the data transmission, combats fading, and further removes correlation between coded bits used to form each modulation symbol. The interleaving may further provide frequency diversity if the coded bits are transmitted over multiple frequency subchannels.

[1092] Puncturer 416 then punctures (i.e., deletes) zero or more of the interleaved coded bits and provides the required number of unpunctured coded bits to modulator 320a. Puncturer 416 may further provide the punctured coded

bits to a buffer 418, which stores these coded bits in case they are needed for an incremental transmission at a later time, as described above.

[1093] In the specific embodiment shown in FIG. 4, modulator 320a includes a symbol mapping element 422, an IFFT 424, and a cyclic prefix generator 426. Symbol mapping element 422 maps the multiplexed pilot data and coded traffic data to modulation symbols for one or more frequency subchannels used for data transmission. One or more modulation schemes may be used for the frequency subchannels, as indicated by the modulation control. For each modulation scheme selected for use, the modulation may be achieved by grouping sets of received bits to form multi-bit symbols and mapping each multi-bit symbol to a point in a signal constellation corresponding to the selected modulation scheme (e.g., QPSK, M-PSK, M-QAM, or some other scheme). Each mapped signal point corresponds to a modulation symbol. Symbol mapping element 422 then provides a vector of (up to N_F) modulation symbols for each transmission symbol period, with the number of modulation symbols in each vector corresponding to the number of (up to N_F) frequency subchannels selected for use for that transmission symbol period.

[1094] IFFT 424 converts each modulation symbol vector into its time-domain representation (which is referred to as an OFDM symbol) using the inverse fast Fourier transform. IFFT 424 may be designed to perform the inverse transform on any number of frequency subchannels (e.g., 8, 16, 32, ... , N_F, ...). In an embodiment, for each OFDM symbol, cyclic prefix generator 426 repeats a portion of the OFDM symbol to form a corresponding transmission symbol. The cyclic prefix ensures that the transmission symbol retains its orthogonal properties in the presence of multipath delay spread, thereby improving performance against deleterious path effects. The transmission symbols from cyclic prefix generator 426 are then provided to transmitter 322 (see FIG. 3) and processed to generate a modulated signal, which is then transmitted from antenna 324.

[1095] Other designs for the transmitter unit may also be implemented and are within the scope of the invention. The implementation of encoder 412, channel interleaver 414, puncturer 416, symbol mapping element 422, IFFT

424, and cyclic prefix generator 426 is known in the art and not described in detail herein.

[1096] The coding and modulation for OFDM and other systems are described in further detail in the aforementioned U.S. Patent Application Serial Nos. 09/826,481, 09/956,449, and 09/854,235, U.S. Patent Application Serial No. 09/776,075, entitled "Coding Scheme for a Wireless Communication System," filed February 1, 2001, and U.S. Patent Application Serial No. 09/993,076, entitled "Multiple-Access Multiple-Input Multiple-Output (MIMO) Communication System," filed November 6, 2001, all assigned to the assignee of the present application and incorporated herein by reference.

[1097] An example OFDM system is described in U.S. Patent Application Serial No. 09/532,492, entitled "High Efficiency, High Performance Communication System Employing Multi-Carrier Modulation," filed March 30, 2000, assigned to the assignee of the present invention and incorporated herein by reference. OFDM is also described in a paper entitled "Multicarrier Modulation for Data Transmission: An Idea Whose Time Has Come," by John A.C. Bingham, IEEE Communications Magazine, May 1990, which is incorporated herein by reference.

[1098] FIG. 5 is a block diagram of an embodiment of a receiver unit 500, which is one embodiment of the receiver portion of receiver system 150a in FIG. 3. The transmitted signal from the transmitter system is received by antenna 352 (FIG. 3) and provided to receiver 354 (which may also be referred to as a front-end processor). Receiver 354 conditions (e.g., filters and amplifies) the received signal, downconverts the conditioned signal to an intermediate frequency or baseband, and digitizes the downconverted signal to provide data samples, which are then provided to a demodulator 360a.

[1099] Within demodulator 360a (FIG. 5), the data samples are provided to a cyclic prefix removal element 510, which removes the cyclic prefix included in each transmission symbol to provide a corresponding recovered OFDM symbol. A FFT 512 then transforms each recovered OFDM symbol using the fast Fourier transform and provides a vector of (up to N_F) recovered modulation symbols for the (up to N_F) frequency subchannels used for data transmission for each transmission symbol period. The recovered modulation symbols from FFT 512

are provided to a demodulation element 514 and demodulated in accordance with one or more demodulation schemes that are complementary to the one or more modulation schemes used at the transmitter system. The demodulated data from demodulation element 514 are then provided to a RX data processor 362a.

[1100] Within RX data processor 362a, the demodulated data is de-interleaved by a de-interleaver 522 in a manner complementary to that performed at the transmitter system, and the de-interleaved data is further decoded by a decoder 524 in a manner complementary to that performed at the transmitter system. For example, a Turbo decoder or a Viterbi decoder may be used for decoder 524 if Turbo or convolutional coding, respectively, is performed at the transmitter unit. The decoded data from decoder 524 represents an estimate of the transmitted data. Decoder 524 may provide the status of each received packet (e.g., received correctly or in error). Decoder 524 may further store demodulated data for packets not decoded correctly, so that this data may be combined with data from a subsequent incremental transmission and decoded.

[1101] As shown in FIG. 5, a channel estimator 516 may be designed to estimate the channel frequency response, $\hat{H}(k)$, and the noise variance, $\hat{N}_0$, and to provide these estimates to controller 370. The channel response and noise variance may be estimated based on the received data samples for the pilot symbols (e.g., based on the FFT coefficients from FFT 512 for the pilot symbols).

[1102] Controller 370 may be designed to implement various aspects and embodiments of the rate selection and the signaling for the incremental transmission. For the rate selection, controller 370 may determine the maximum data rate that may be used for the given channel conditions based on the metric Ψ, as described above. For incremental transmission, controller 370 may provide an ACK or a NACK for each received transmission for a given packet, which may be used at the transmitter system to transmit an additional portion of the packet if the packet cannot be recovered correctly at the receiver system.

[1103] FIGS. 1A and 3 show a simple design whereby the receiver sends back the rate for the data transmission. Other designs may also be implemented and are within the scope of the invention. For example, the channel estimates may be sent to the transmitter (instead of the rate), which may then determine the rate for the data transmission based on the received channel estimates.

[1104] The rate selection and incremental transmission techniques described herein may be implemented using various designs. For example, channel estimator 516 in FIG. 5 used to derive and provide the channel estimates may be implemented by various elements in the receiver system. Some or all of the processing to determine the rate may be performed by controller 370 (e.g., with one or more look-up tables stored in memory 372). Other designs for performing the rate selection and incremental transmission may also be contemplated and are within the scope of the invention.

[1105] The rate selection and incremental transmission techniques described herein may be implemented by various means. For example, these techniques may be implemented in hardware, software, or a combination thereof. For a hardware implementation, some of the elements used to implement the rate selection and/or incremental transmission may be implemented within one or more application specific integrated circuits (ASICs), digital signal processors (DSPs), digital signal processing devices (DSPDs), programmable logic devices (PLDs), field programmable gate arrays (FPGAs), processors, controllers, micro-controllers, microprocessors, other electronic units designed to perform the functions described herein, or a combination thereof.

[1106] For a software implementation, some portions of the rate selection and/or incremental transmission may be implemented with modules (e.g., procedures, functions, and so on) that perform the functions described herein. The software codes may be stored in a memory unit (e.g., memory 332 or 372 in FIG. 3) and executed by a processor (e.g., controller 330 or 370). The memory unit may be implemented within the processor or external to the processor, in which case it can be communicatively coupled to the processor via various means as is known in the art.

Constrained Capacity Rate Adaptation (CCRA) Algorithm

[1107] In an alternate embodiment, the rate adaptation scheme for orthogonal frequency division multiplexing (OFDM) systems provided hereinabove is adapted to a practical environment, wherein the algorithm adjusts the ideal case to reflect known practicalities of the system. Note that the algorithm is provided in detail again for clarity of understanding. Such extension may involve a back-off modification that lends the scheme for practical implementation. The use of the back-off mechanism is particularly important wherein system configuration and other system considerations require adjustment. In other words, within one system certain conditions may incur a back-off modification, while others do not. The back-off mechanism is intended to coordinate the channel model to the practical application. Situations in which the back-off may be desirable include, but are not limited to: 1) channel coding technique; 2) imperfect channel estimate; and/or 3) frequency and/or phase-offset irregularities.

[1108] Consider an OFDM system according to one embodiment as described hereinabove with N subcarriers in a multipath fading channel. The algorithm assumes the knowledge of the channel response across all subcarriers $\{h(k), k=1,2,\Lambda\ ,N\}$, and the noise variance N_o at the receiver. Given a set $R=\{r_p, p=1,2,\Lambda\ ,P\}$ of data rates supported by the transmitter each defined by a modulation scheme C_p and a code rate Rc_p. Given also a corresponding set $S=\{s_p, p=1,2,\Lambda\ ,P\}$ of the required SNR for predetermined PER level (say 1%). The goal is to find out the maximum achievable rate $r_{max} \in R$ that can be supported by the channel for a given realization. A first algorithm is defined as in FIG. 6, and is referred to as the Constrained Capacity Rate Adaptation (CCRA) algorithm.

[1109] The CCRA algorithm, according to an exemplary embodiment, is defined by a process 600, wherein an index *p* is initialized at step 602. The index *p* corresponds to the available encoding rates in a given communication transmitter, and is given as *p*=1, 2, ..., P, wherein P is the total number of distinct available rates. At step 602 the index *p* is set equal to P, wherein P corresponds to the highest rate in the set R of data rates. At step 604, the process calculates the constrained capacity *x*, given as:

$$x = \sum_{k=1}^{N} f(h(k), N_o, C(r_p)) \quad \text{Eq (12)}$$

wherein f is the constrained capacity function, and $C(r_p)$ is the constellation size (modulation) at rate r_p. The calculation process 650 for the constrained capacity x is illustrated in FIG. 7B, wherein the function f for evaluating the constrained capacity is determined at step 652. The constrained capacity *x* is then calculated at step 654 according to Equ. (12). The value of *x* is based on a mean of the channel condition.

[1110] Returning to FIG. 7A, at step 606, the process calculates an equivalent SNR in the AWGN channel, denoted as Ψ, given as:

$$\Psi = g(x) = f^{-1}(x) \quad \text{Eq (13)}$$

wherein $g(x)$ is the inverse function of $f(x)$. Note that Equ. (13) is consistent with Equ. (9). At decision diamond 608, if $\Psi > s_p$ then the maximum available data rate is set equal to the current data rate, i.e., rate corresponding to p ($r_{max}=r_p$). Else, the index *p* is decremented, i.e., $p = p-1$, and processing decrements *p* at step 612 and returns to step 604.

[1111] Evaluation of the performance of the CCRA algorithm involves a comparison to an optimal rate selection process. The optimal selection is a non-practical system which basically tests every possible rate (for a given channel realization) and selects the highest rate for a given PER, e.g., PER<1%. It is expected that the algorithm will not beat the optimal model, as the algorithm is not expected to support a higher throughput without violating the designated PER. The best practical algorithm is the one that supports a throughput slightly less than the optimal one with 1% PER.

[1112] The back-off could be necessitated as the result of the CCRA algorithm being based on a capacity formula which is by itself an over estimation of the supported rate, as the capacity formula provides the rate supported by a perfect system employing perfect codes, which is typically not attainable in practice. In other words, the capacity is an upper bound on the achievable rate by the channel. Hence, an educated adjustment, i.e., back-off, of the resultant rate produced by the CCRA algorithm may be desired.

Similarly, back-off may be desirable when a system supports a variety of data rates wherein imperfections may be incurred during operation.

Modified-Constrained Capacity Rate Adaptation (M-CCRA) Algorithm

[1113] Note that S is the set of SNRs corresponding to 1% PER for each available rate in a practical system. It is also possible to evaluate the theoretical ideal values for the SNR based on the capacity formula. Let the set of ideal SNR to be $S_{cap} = \{s_{cap,p},\ p = 1,2,\Lambda\ ,P\}$. Note that $S_{cap,p} < S_p \forall\ \ p$ since $s_{cap,p}$ is the required SNR for an ideal system while s_p is the required SNR for a practical system. Define the set $\Omega = \{\Delta_p = s_p - s_{cap,p}, p = 1,2,\Lambda\ ,P\}$. Then Δ_p represents the additional required SNR for a practical system to overcome any imperfections in the system.

[1114] When the constrained capacity x in Equ. (13) lies between two consecutive rates, let's say r_p and r_{p+1}, a corresponding adjustment in SNR may be made using the two levels are Δ_p and Δ_{p+1}, respectively. To determine the adjustment for Ψ, the following equations may be applied:

$$\Delta\Psi = \frac{\Delta_p(r_{p+1} - x) + \Delta_{p+1}(x - r_p)}{r_{p+1} - r_p} \qquad \text{Eq (14)}$$

$$\Delta\Psi = \max(\Delta_p, \Delta_{p+1}) \qquad \text{Eq (15)}$$

Either of the calculations of Equ. (14) or Equ. (15) may then be applied to the CCRA algorithm in addition to step 606 to replace Ψ with $\Psi - \Delta\Psi$. In other words, with reference to FIG. 2, at step 220 replace the comparison of Ψ to SNR with a comparison of $\Psi - \Delta\Psi$ to SNR. The Modified-CCRA algorithm is illustrated in FIG. 7A. The process 700 starts with initialization of the index *p* at step 702. The constrained capacity is then determined at step 704, using a calculation as given in Equ. (6) or Equ. (12). The SNR Ψ is calculated at step 706 as in Equ. (9) or Equ. (13). The modification of Equ. (14) or Equ. (15) is applied at step 708 to generate Ψ'. At decision diamond 710, the modified SNR Ψ' is compared to s_p, wherein if Ψ' is greater than sp, the maximum rate

is set to the rate identified by the current value of index *p*. Else, the index *p* is decremented at step 714 and processing returns to step 704.

[1115] FIG. 8 illustrates performance of the CCRA algorithm compared to an optimal or ideal rate selection. Note that in the CCRA algorithm provides a solution having throughput close to the ideal solution, while achieving the desired PER level, which in the exemplary embodiment is 1% PER.

[1116] Those of skill in the art would understand that information and signals may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

[1117] Those of skill would further appreciate that the various illustrative logical blocks, modules, circuits, and algorithm steps described in connection with the embodiments disclosed herein may be implemented as electronic hardware, computer software, or combinations of both. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. Skilled artisans may implement the described functionality in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the present invention.

[1118] The various illustrative logical blocks, modules, and circuits described in connection with the embodiments disclosed herein may be implemented or performed with a general purpose processor, a digital signal processor (DSP), an application specific integrated circuit (ASIC), a field programmable gate array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general purpose processor may be a microprocessor, but in the alternative, the processor may be any conventional

processor, controller, microcontroller, or state machine. A processor may also be implemented as a combination of computing devices, e.g., a combination of a Digital Signal Processor (DSP) and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration.

[1119] The steps of a method or algorithm described in connection with the embodiments disclosed herein may be embodied directly in hardware, in a software module executed by a processor, or in a combination of the two. A software module may reside in Random Access Memory (RAM), FLASH memory, Read-Only Memory (ROM), Erasable Programmable ROM (EPROM), Electrically EPROM (EEPROM), registers, hard disk, a removable disk, a CD-ROM, or any other form of storage medium known in the art. An exemplary storage medium is coupled to the processor such the processor can read information from, and write information to, the storage medium. In the alternative, the storage medium may be integral to the processor. The processor and the storage medium may reside in an Application Specific Integrated Circuit (ASIC). The ASIC may reside in a user terminal. In the alternative, the processor and the storage medium may reside as discrete components in a user terminal.

[1120] The previous description of the disclosed embodiments is provided to enable any person skilled in the art to make or use the present invention. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without departing from the spirit or scope of the invention. Thus, the present invention is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

[1121] WHAT IS CLAIMED IS:

CLAIMS

1. A method for determining a data rate for a data transmission over a communication channel in a wireless communication system, comprising:

identifying a set of parameters for the data transmission;

estimating one or more characteristics of the communication channel;

deriving a metric for an equivalent channel based on the set of parameters and the one or more estimated channel characteristics;

adjusting the metric to form an adjusted metric, wherein adjusting is done according to a back-off factor, the back-off factor designed to minimize Packet Error Rate (PER);

determining a threshold signal quality required for the equivalent channel to support a particular data rate;

comparing the adjusted metric to the threshold signal quality;

adjusting the threshold signal quality;

selecting a data rate in response; and

indicating whether or not the particular data rate is supported by the communication channel based on the metric and the threshold signal quality.

2. The method of claim 1, wherein the metric is a function of Signal-to-Noise Ratio (SNR).

3. The method of claim 1, wherein the adjusting the metric further comprises:

determining if a back-off factor is to be applied to the metric;

if the back-off factor is to be applied, adjusting the metric; and

if the back-off factor is not to be applied, retaining the metric.

4. The method of claim 1, wherein the deriving the metric includes

determining an equivalent data rate for the equivalent channel based on a first function, the set of parameters, and the one or more estimated channel characteristics, and

wherein the metric is derived based on a second function, the equivalent data rate, and the particular modulation scheme.

5. A receiver unit in a wireless communication system, comprising:

a channel estimator operative to derive estimates of one or more characteristics of a communication channel used for a data transmission;

a rate selector operative to receive channel estimates from the channel estimator and a set of parameters indicative of a particular rate for the data transmission, derive a metric for an equivalent channel, determine a threshold signal quality required for the equivalent channel to support the particular rate, and indicate whether or not the particular rate is supported by the communication channel based on the metric and the threshold signal quality; and

a metric adjuster operative to adjust the metric using a predetermined back-off factor.

6. The receiver unit of claim 5, further comprising:

a decoder operative to provide a status of each received transmission for a particular packet of data; and

a controller operative to provide feedback information comprised of the particular rate and an indication of the packet status.

7. An apparatus in a wireless communication system, comprising:

means for identifying a set of parameters for the data transmission;

means for estimating one or more characteristics of the communication channel;

means for deriving a metric for an equivalent channel based on the set of parameters and the one or more estimated channel characteristics;

means for adjusting the metric to form an adjusted metric, wherein adjusting is done according to a back-off factor, the back-off factor designed to minimize Packet Error Rate (PER);

means for determining a threshold signal quality required for the equivalent channel to support a particular data rate;

means for comparing the adjusted metric to the threshold signal quality;

means for adjusting the threshold signal quality;

means for selecting a data rate in response; and

means for indicating whether or not the particular data rate is supported by the communication channel based on the metric and the threshold signal quality.

8. The apparatus of claim 7, further comprising:

means for determining an equivalent data rate for the equivalent channel based on a first function, the set of parameters, and the channel estimates, and

wherein the metric is derived based on a second function, the equivalent data rate, and a particular modulation scheme associated with the particular rate.

9. The apparatus of claim 8, further comprising:

means for storing one or more tables for the first function.

10. A method for determining a data rate for a data transmission over a communication channel in a wireless communication system, comprising:

estimating one or more characteristics of the communication channel;

deriving a metric for an equivalent channel based on the set of parameters and the one or more estimated channel characteristics;

adjusting the metric to form an adjusted metric, wherein adjusting is done according to a back-off factor, the back-off factor designed to minimize Packet Error Rate (PER);

determining a threshold signal quality required for the equivalent channel to support a particular data rate;

comparing the adjusted metric to the threshold signal quality; and

selecting a data rate in response to a result of comparing the adjusted metric to the threshold signal quality.

11. The method as in claim 10, wherein the metric is Signal-to-Noise Ratio.

12. The method as in claim 10, wherein adjusting the metric comprises:

determining if the back-off factor is to be applied to the metric;

applying the back-off factor according to determining if the back-off factor is to be applied to the metric.

13. An apparatus for determining a data rate for a data transmission over a communication channel in a wireless communication system, comprising:

means for estimating one or more characteristics of the communication channel;

means for deriving a metric for an equivalent channel based on the set of parameters and the one or more estimated channel characteristics;

means for adjusting the metric to form an adjusted metric, wherein adjusting is done according to a back-off factor, the back-off factor designed to minimize Packet Error Rate (PER);

means for determining a threshold signal quality required for the equivalent channel to support a particular data rate;

means for comparing the adjusted metric to the threshold signal quality; and

means for selecting a data rate in response to a result of comparing the adjusted metric to the threshold signal quality.

14. A computer program for determining a data rate for a data transmission over a communication channel in a wireless communication system, the computer program comprising:

a first set of instructions for estimating one or more characteristics of the communication channel;

a second set of instructions for deriving a metric for an equivalent channel based on the set of parameters and the one or more estimated channel characteristics;

a third set of instructions for adjusting the metric to form an adjusted metric, wherein adjusting is done according to a back-off factor, the back-off factor designed to minimize Packet Error Rate (PER);

a fourth set of instructions for determining a threshold signal quality required for the equivalent channel to support a particular data rate;

a fifth set of instructions for comparing the adjusted metric to the threshold signal quality; and

a sixth set of instructions for selecting a data rate in response to a result of comparing the adjusted metric to the threshold signal quality.

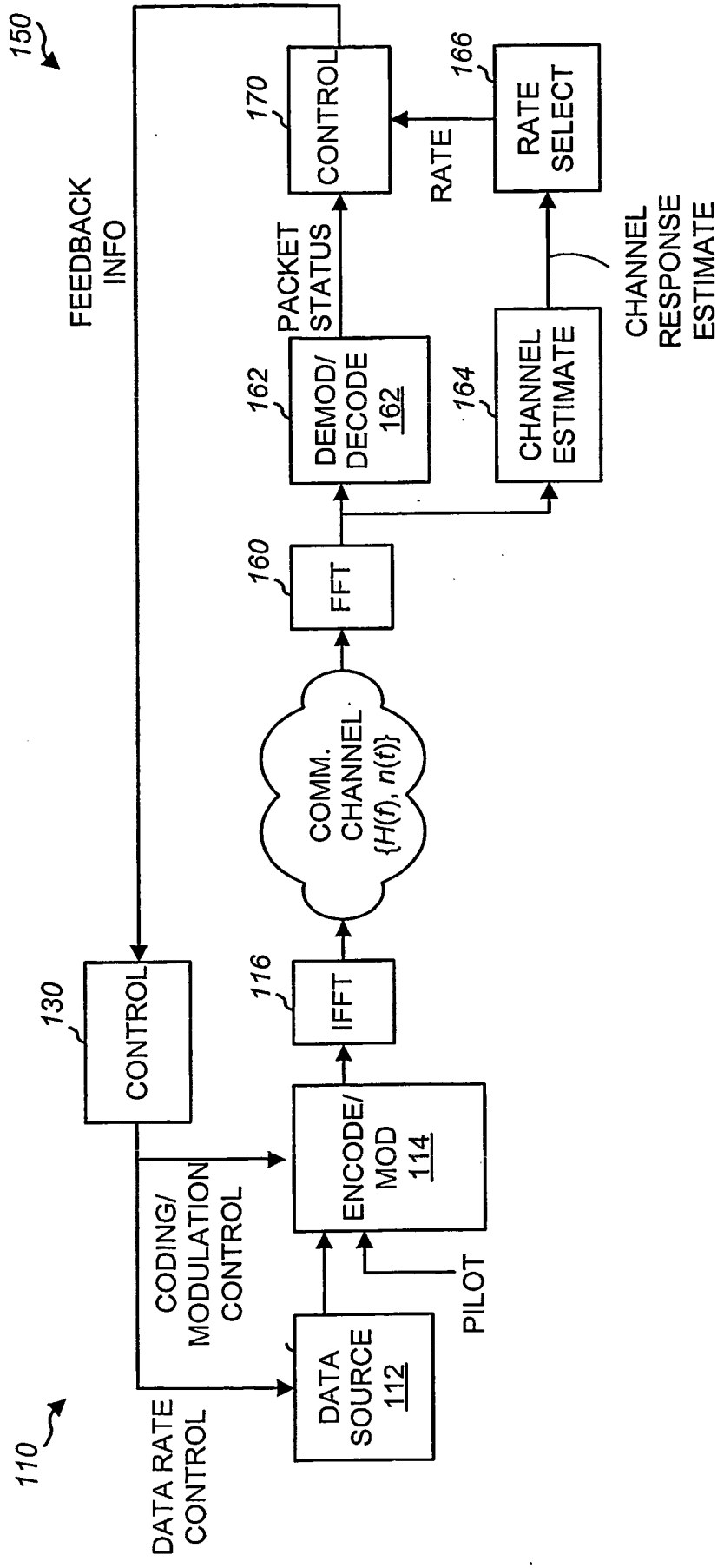
150
FEEDBACK INFO
170
CONTROL
166
RATE SELECT
RATE
PACKET STATUS
162
DEMOD/ DECODE 162
164
CHANNEL ESTIMATE
CHANNEL RESPONSE ESTIMATE
160
FFT
COMM. CHANNEL {H(f), n(f)}
130
CONTROL
116
IFFT
CODING/ MODULATION CONTROL
ENCODE/ MOD 114
PILOT
DATA SOURCE 112
110
DATA RATE CONTROL

FIG. 1A

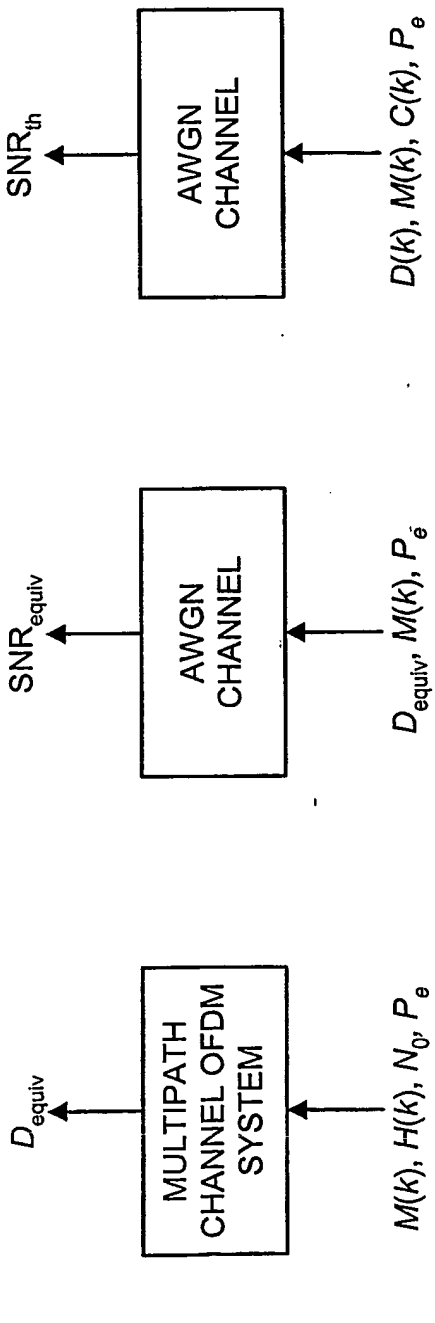
MULTIPATH CHANNEL OFDM SYSTEM
D_{equiv}
$M(k)$, $H(k)$, N_0, P_e
$D_{equiv}=f[x]$, $x=\{H(k), N_0, M(k)\}$
AWGN CHANNEL
SNR_{equiv}
D_{equiv}, $M(k)$, P_e
$SNR_{equiv} = g[D_{equiv}, M(k)]$
AWGN CHANNEL
SNR_{th}
$D(k)$, $M(k)$, $C(k)$, P_e

FIG. 1B

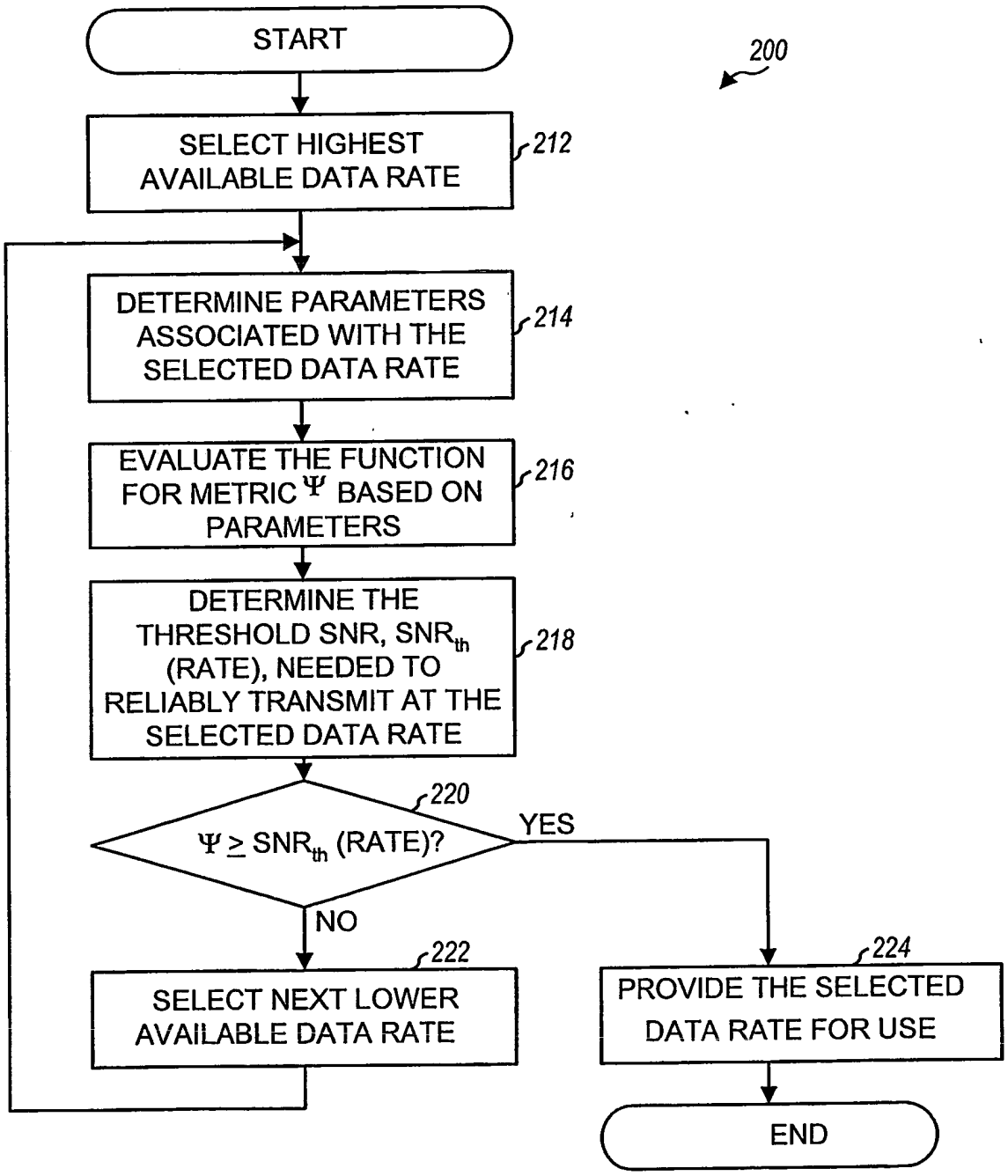
START
200
SELECT HIGHEST AVAILABLE DATA RATE
212
DETERMINE PARAMETERS ASSOCIATED WITH THE SELECTED DATA RATE
214
EVALUATE THE FUNCTION FOR METRIC Ψ BASED ON PARAMETERS
216
DETERMINE THE THRESHOLD SNR, SNR$_{th}$ (RATE), NEEDED TO RELIABLY TRANSMIT AT THE SELECTED DATA RATE
218
220
Ψ ≥ SNR$_{th}$ (RATE)?
YES
NO
222
SELECT NEXT LOWER AVAILABLE DATA RATE
224
PROVIDE THE SELECTED DATA RATE FOR USE
END

FIG. 2

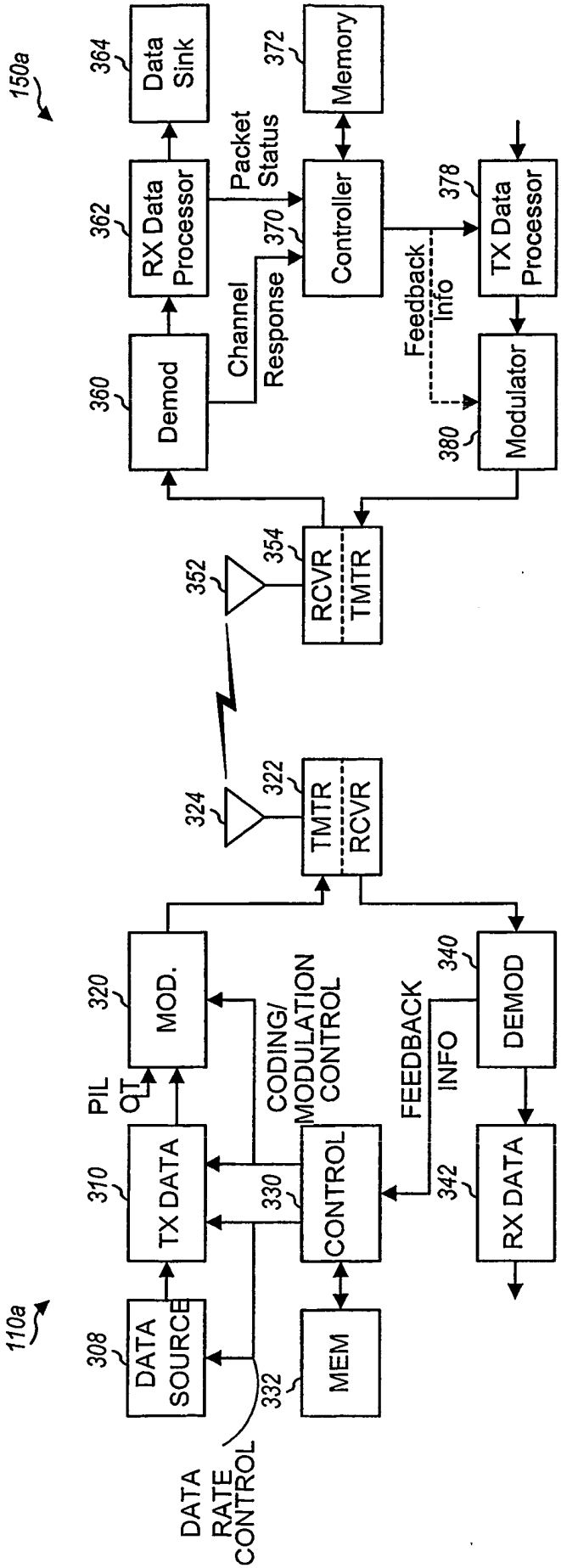
150a
364
Data Sink
372
Memory
Packet Status
362
RX Data Processor
370
Controller
378
TX Data Processor
Channel Response
Feedback Info
360
Demod
380
Modulator
352
354
RCVR
TMTR
324
322
TMTR
RCVR
110a
320
MOD.
340
DEMOD
PIL
QT
CODING/ MODULATION CONTROL
FEEDBACK INFO
310
TX DATA
330
CONTROL
342
RX DATA
308
DATA SOURCE
332
MEM
DATA RATE CONTROL

FIG. 3

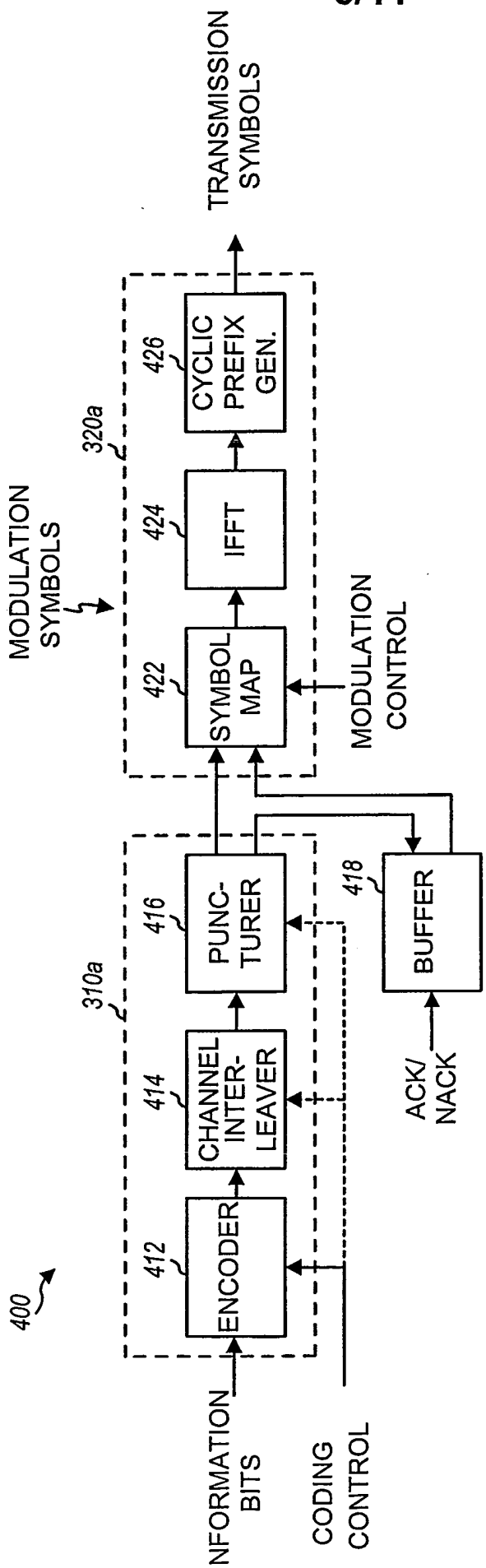
400
INFORMATION BITS
CODING CONTROL
310a
412 ENCODER
414 CHANNEL INTER-LEAVER
416 PUNC-TURER
418 BUFFER
ACK/ NACK
320a
422 SYMBOL MAP
424 IFFT
426 CYCLIC PREFIX GEN.
MODULATION SYMBOLS
MODULATION CONTROL
TRANSMISSION SYMBOLS

FIG. 4

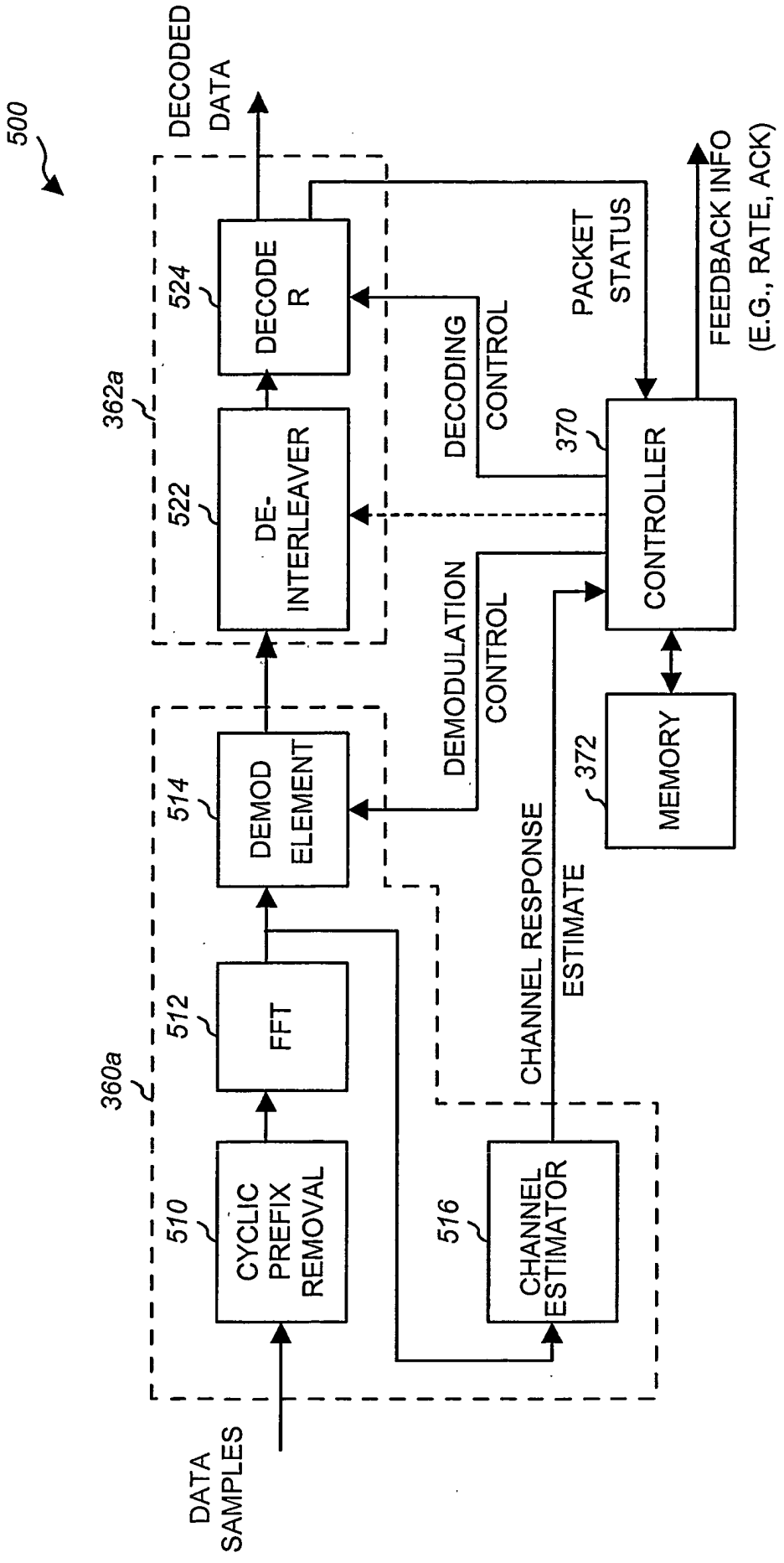
500
DECODED DATA
524
DECODE R
362a
522
DE-INTERLEAVER
514
DEMOD ELEMENT
512
FFT
360a
510
CYCLIC PREFIX REMOVAL
516
CHANNEL ESTIMATOR
DATA SAMPLES
DECODING CONTROL
DEMODULATION CONTROL
CHANNEL RESPONSE ESTIMATE
PACKET STATUS
370
CONTROLLER
372
MEMORY
FEEDBACK INFO (E.G., RATE, ACK)

FIG. 5

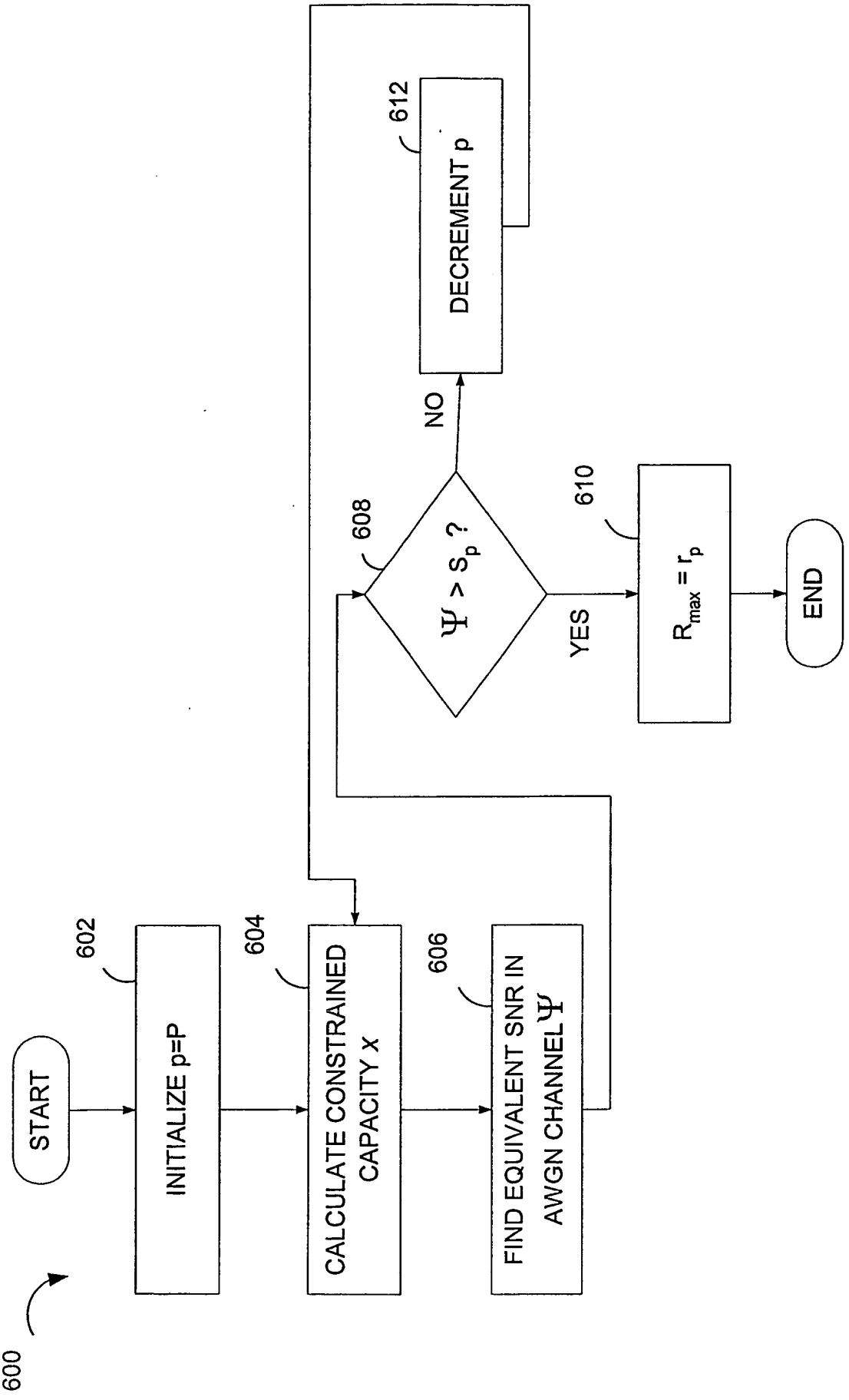
600
START
602
INITIALIZE p=P
604
CALCULATE CONSTRAINED CAPACITY X
606
FIND EQUIVALENT SNR IN AWGN CHANNEL Ψ
608
Ψ > s_p ?
NO
612
DECREMENT p
YES
610
R_{max} = r_p
END

FIG. 6

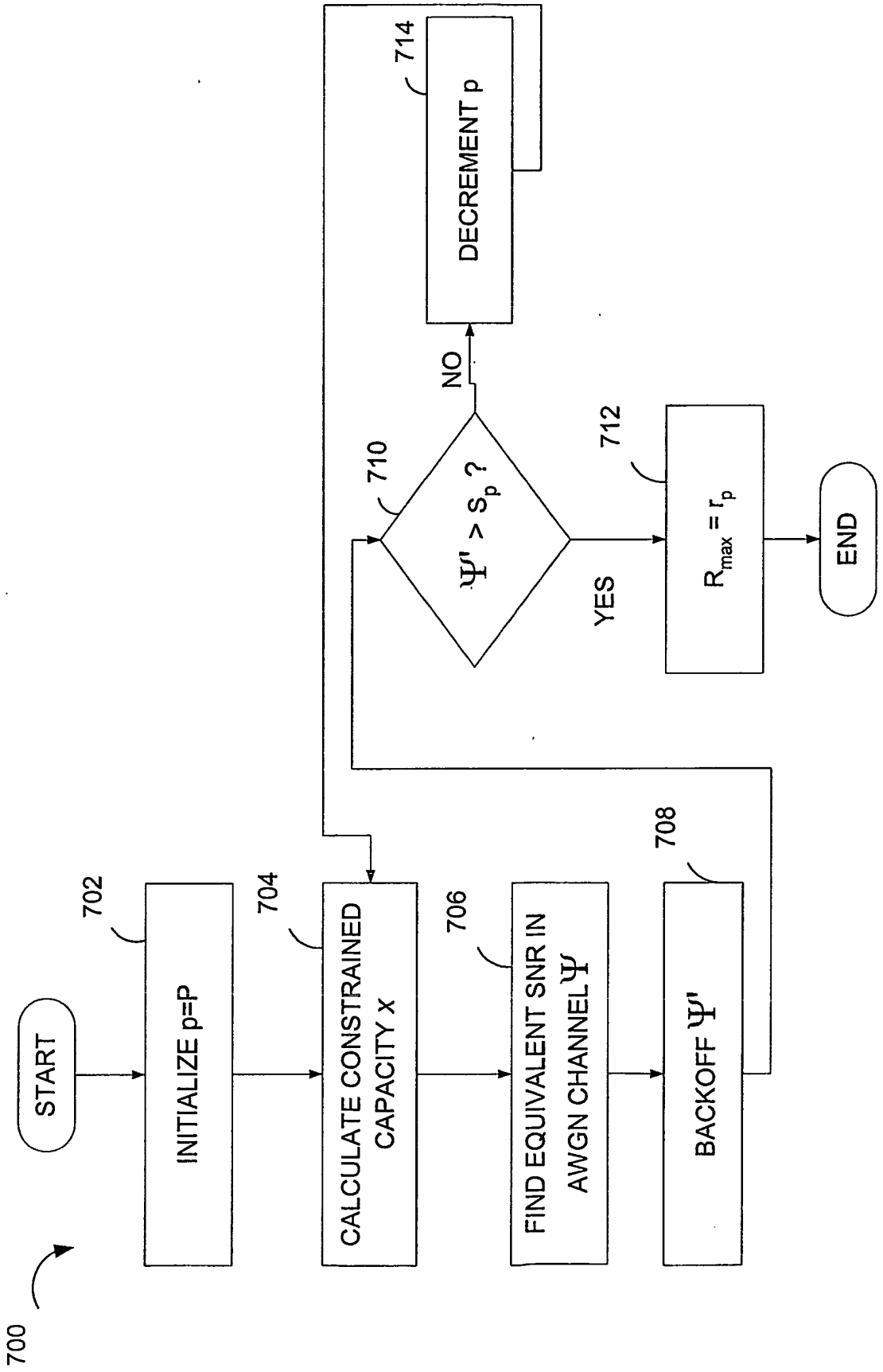
700
START
INITIALIZE p=P
702
CALCULATE CONSTRAINED CAPACITY x
704
FIND EQUIVALENT SNR IN AWGN CHANNEL Ψ
706
BACKOFF Ψ'
708
Ψ' > s_p ?
710
NO
YES
DECREMENT p
714
R_max = r_p
712
END

FIG. 7A

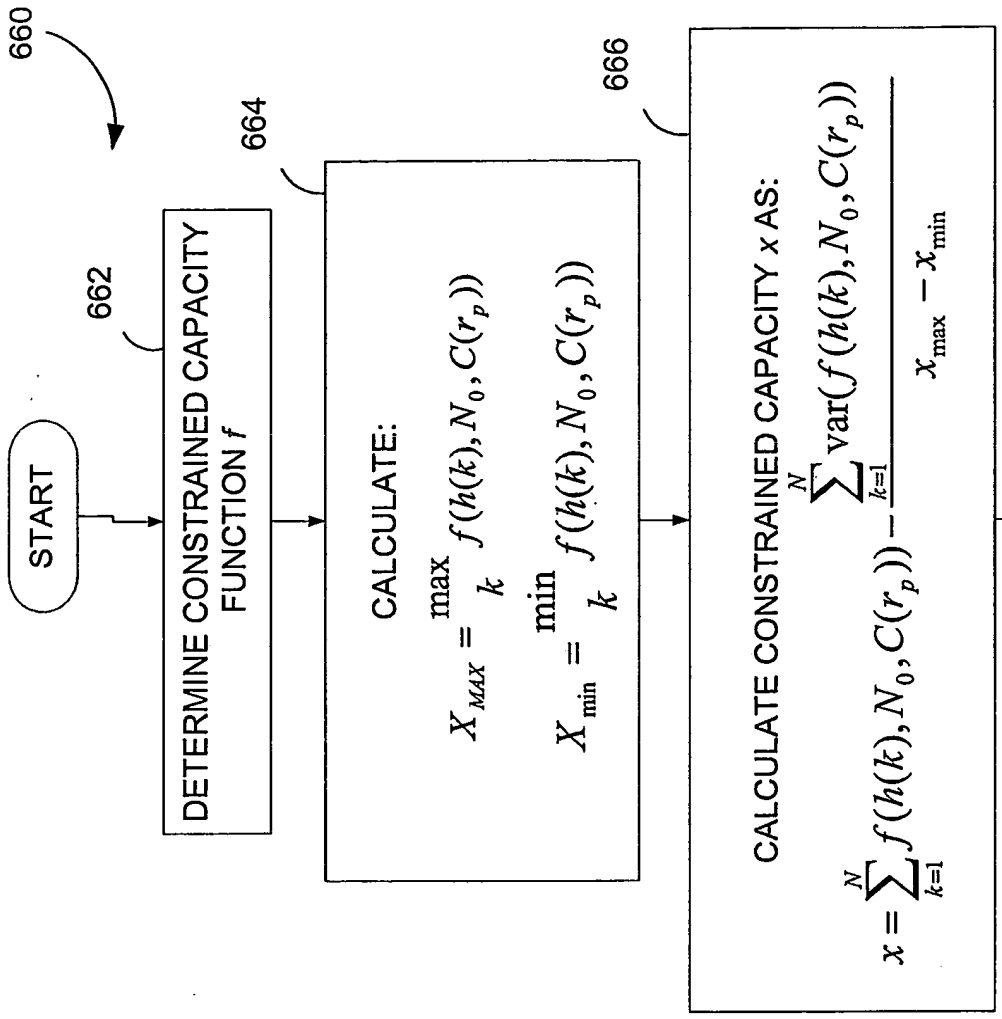
660
START
662
DETERMINE CONSTRAINED CAPACITY FUNCTION f
664
CALCULATE:
$X_{MAX} = \max_k f(h(k), N_0, C(r_p))$
$X_{\min} = \min_k f(h(k), N_0, C(r_p))$
666
CALCULATE CONSTRAINED CAPACITY x AS:
$x = \sum_{k=1}^{N} f(h(k), N_0, C(r_p)) - \frac{\sum_{k=1}^{N} \mathrm{var}(f(h(k), N_0, C(r_p)))}{x_{\max} - x_{\min}}$
END

FIG. 7C

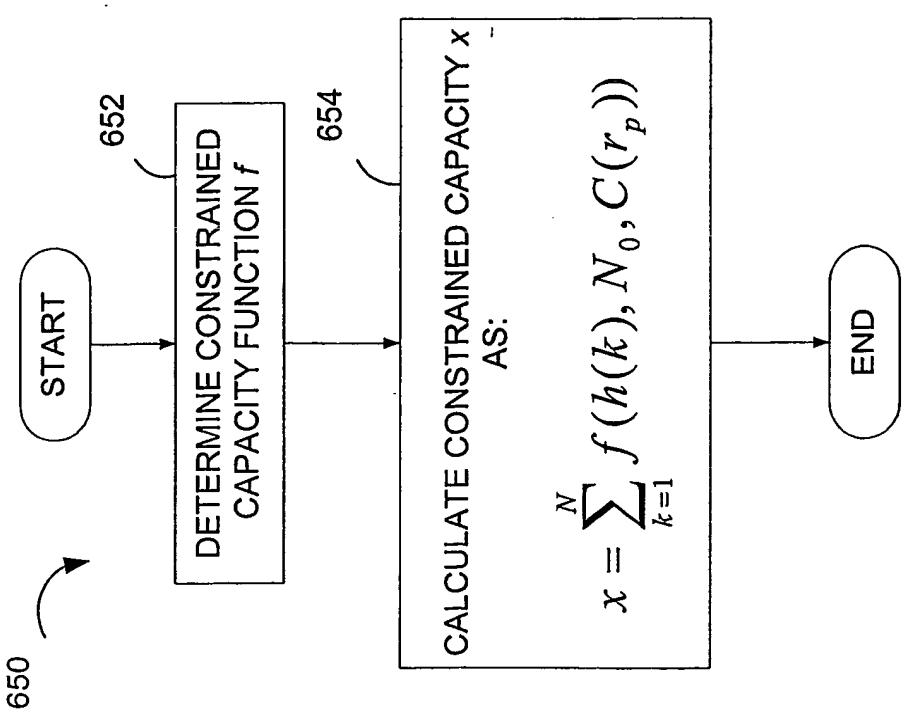
650
START
652
DETERMINE CONSTRAINED CAPACITY FUNCTION f
654
CALCULATE CONSTRAINED CAPACITY x AS:
$x = \sum_{k=1}^{N} f(h(k), N_0, C(r_p))$
END

FIG. 7B

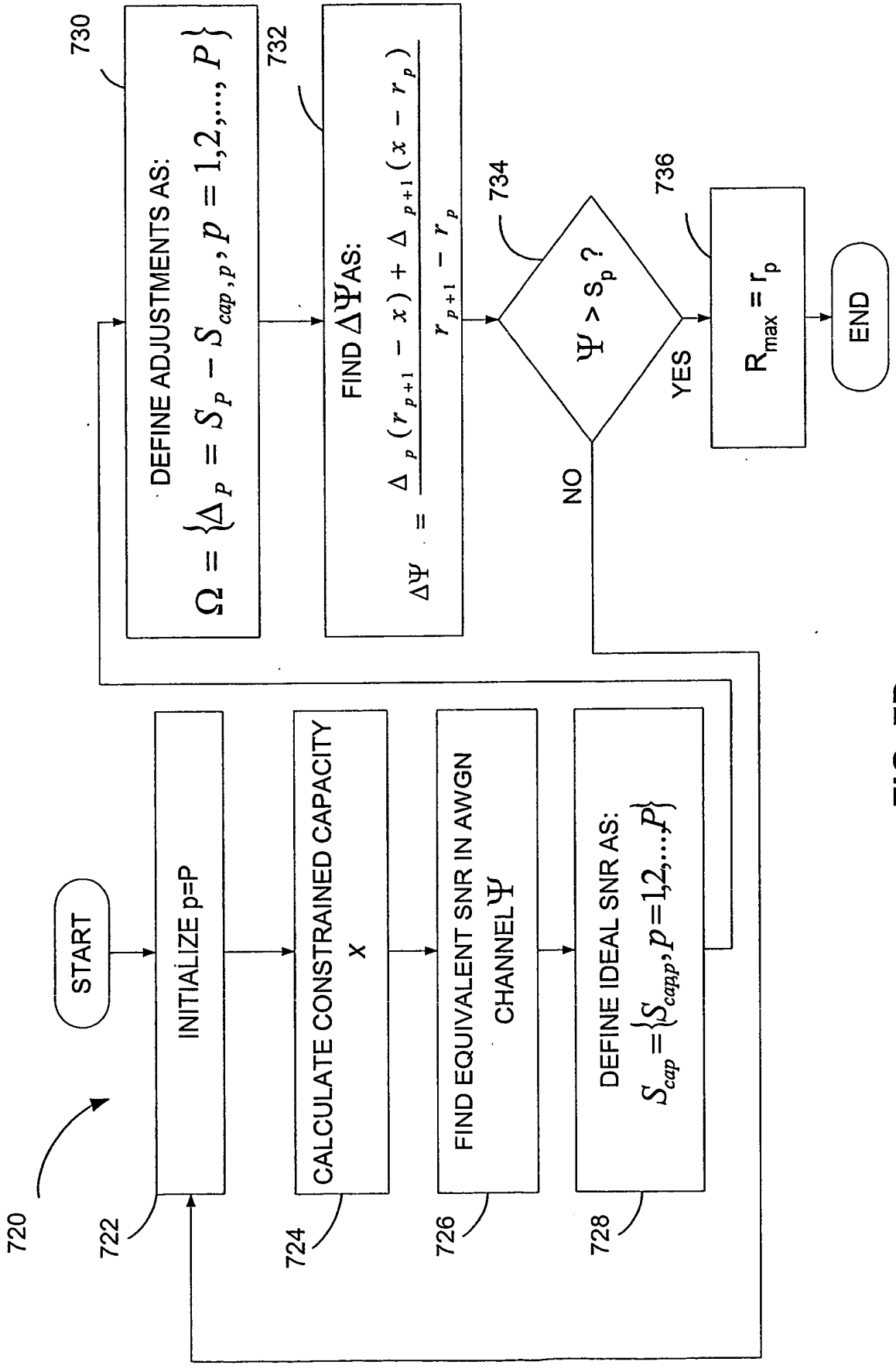
START
INITIALIZE p=P
CALCULATE CONSTRAINED CAPACITY X
FIND EQUIVALENT SNR IN AWGN CHANNEL Ψ
DEFINE IDEAL SNR AS:
$S_{cap} = \{S_{cap,p}, p=1,2,\ldots,P\}$
DEFINE ADJUSTMENTS AS:
$\Omega = \{\Delta_p = S_p - S_{cap,p}, p = 1,2,\ldots, P\}$
FIND $\Delta\Psi$ AS:
$\Delta\Psi = \frac{\Delta_p (r_{p+1} - x) + \Delta_{p+1}(x - r_p)}{r_{p+1} - r_p}$
Ψ > s_p ?
NO
YES
$R_{max} = r_p$
END
720
722
724
726
728
730
732
734
736

FIG. 7D

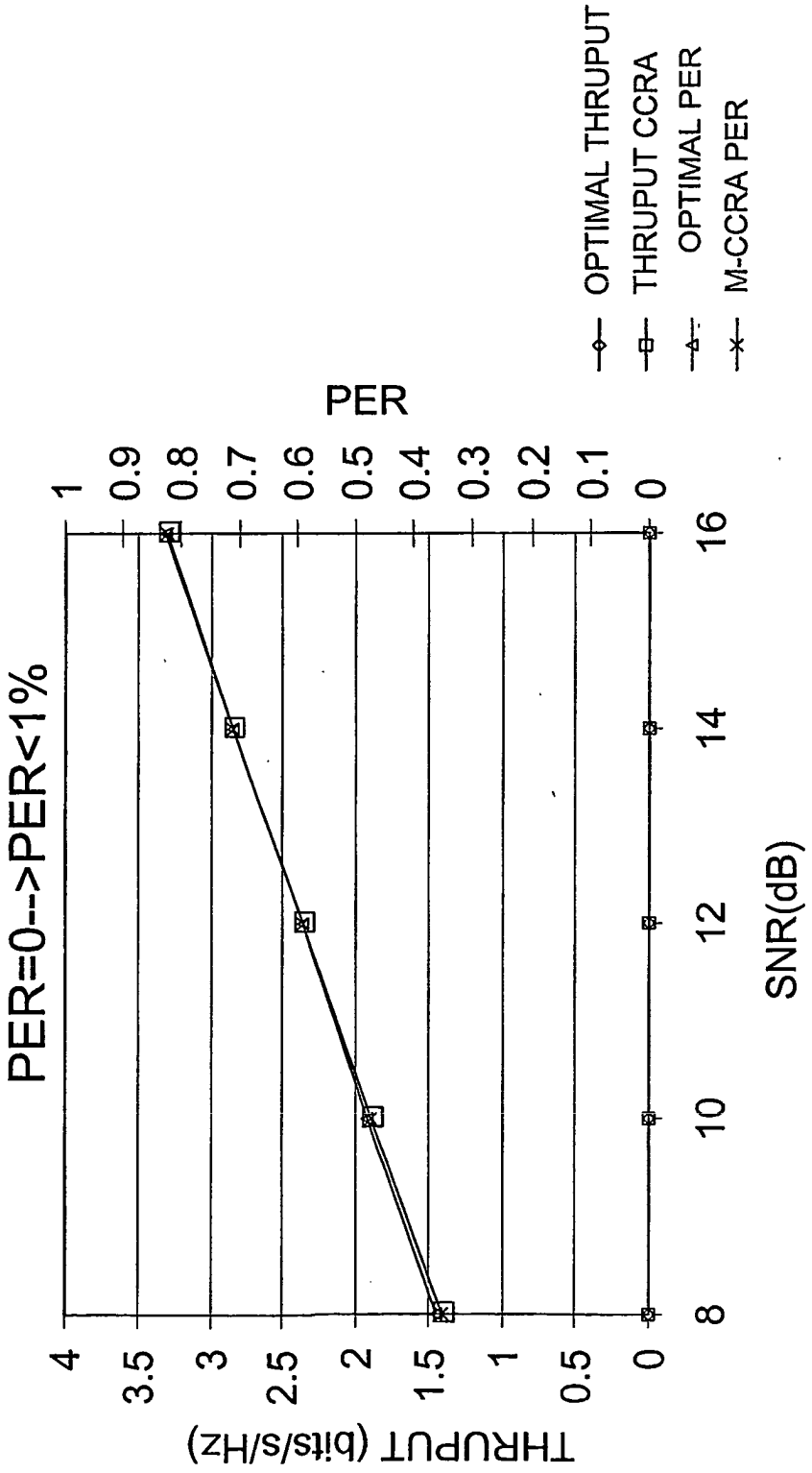
OPTIMAL THRUPUT
THRUPUT CCRA
OPTIMAL PER
M-CCRA PER
PER
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
PER=0-->PER<1%
THRUPUT (bits/s/Hz)
4
3.5
3
2.5
2
1.5
1
0.5
0
8
10
12
14
16
SNR(dB)

FIG. 8